Global Warming Potential

Life Cycle Assessment of Electrical and Thermal Energy Systems for Commercial Buildings*

Ayat Osman and Robert Ries**

Department of Civil and Environmental Engineering, University of Pittsburgh, Benedum Hall 949, Pittsburgh, PA 15261 USA

** **Corresponding author** (robries@pitt.edu)

DOI: http://dx.doi.org/10.1065/lca2007.02.310

Please cite this paper as: Osman A, Ries R (2007): Life Cycle Assessment of Electrical and Thermal Energy Systems for Commercial Buildings. Int J LCA 12 (5) 308–316

Abstract

Background, Aim and Scope. The objective of this life cycle assessment (LCA) study is to develop LCA models for energy systems in order to assess the potential environmental impacts that might result from meeting energy demands in buildings. The scope of the study includes LCA models of the average electricity generation mix in the USA, a natural gas combined cycle (NGCC) power plant, a solid oxide fuel cell (SOFC) cogeneration system; a microturbine (MT) cogeneration system; an internal combustion engine (ICE) cogeneration system; and a gas boiler.

Methods. LCA is used to model energy systems and obtain the life cycle environmental indicators that might result when these systems are used to generate a unit energy output. The intended use of the LCA analysis is to investigate the operational characteristics of these systems while considering their potential environmental impacts to improve building design using a mixed integer linear programming (MILP) optimization model.

Results. The environmental impact categories chosen to assess the performance of the energy systems are global warming potential (GWP), acidification potential (AP), tropospheric ozone precursor potential (TOPP), and primary energy consumption (PE). These factors are obtained for the average electricity generation mix, the NGCC, the gas boiler, as well as for the cogeneration systems at different part load operation. The contribution of the major emissions to the emission factors is discussed.

Discussion. The analysis of the life cycle impact categories indicates that the electrical to thermal energy production ratio has a direct influence on the value of the life cycle PE consumption factors. Energy systems with high electrical to thermal ratios (such as the SOFC cogeneration systems and the NGCC power plant) have low PE consumption factors, whereas those with low electrical to thermal ratios (such as the MT cogeneration system) have high PE consumption factors. In the case of GWP, the values of the life cycle GWP obtained from the energy systems do not only depend on the efficiencies of the systems but also on the origins of emissions contributing to GWP. When evaluating the life cycle AP and TOPP, the types of fuel as well as the combustion characteristics of the energy systems are the main factors that influence the values of AP and TOPP.

Conclusions. An LCA study is performed to evaluate the life cycle emission factors of energy systems that can be used to meet the energy demand of buildings. Cogeneration systems produce utilizable thermal energy when used to meet a certain electrical demand which can make them an attractive alternative to conventional systems. The life cycle GWP, AP, TOPP and PE consumption factors are obtained for utility systems as well as cogeneration systems at different part load operation levels for the production of one kWh of energy output.

Recommendations and Perspectives. Although the emission factors vary for the different energy systems, they are not the only factors that influence the selection of the optimal system for building operations. The total efficiencies of the system play a significant part in the selection of the desirable technology. Other factors, such as the demand characteristics of a particular building, influence the selection of energy systems.

The emission factors obtained from this LCA study are used as coefficients of decision variables in the formulation of an MILP to optimize the selection of energy systems based on environmental criteria by taking into consideration the system efficiencies, emission characteristics, part load operation, and building energy demands. Therefore, the emission factors should not be regarded as the only criteria for choosing the technology that could result in lower environmental impacts, but rather one of several factors that determine the selection of the optimum energy system.

Keywords: Building energy systems; cogeneration; electrical energy system; energy demands in buildings; internal combustion engine (ICE) cogeneration system; microturbine (MT) cogeneration system; modeling energy systems; natural gas combined cycle (NGCC) power plant; optimization; primary energy consumption (PE); solid oxide fuel cell (SOFC) cogeneration system; thermal energy system; tropospheric ozone precursor potential (TOPP); warming potential (GWP)

Introduction

In building design, energy use is an issue that is related to notable resource use and environmental quality concerns. In order to reduce environmental impact of building energy use, it is important to address strategies for reducing energy use, such as improving the building envelope, high efficiency lighting and daylighting, and heating, ventilating, and air conditioning (HVAC) system design and selection. Some of the fundamental decision making questions also relate to

* **ESS-Submission Editor:** Arpad Horvath (horvath@ce.berkeley.edu)

determining what is (are) the most beneficial and cost effective energy source(s) that can be used to meet the energy demand of the building. Some of the significant factors that influence the selection of energy systems in buildings are the energy resource type, the electrical and thermal efficiencies of the systems including the electrical to thermal production ratios of cogeneration systems, and the load requirements of a particular building. One way of approaching the problem is to model the available options using linear programming. Linear programming is an effective tool for determining the values of a set of decision variables that can take on a large set of possible values in order to optimize a linear objective subject to linear constraints. The majority of previous work has focused on the optimization of the operation of a utility plant by minimizing cost and maximizing revenues [1–4]. Several studies addressed the effects of process parameters on improving the efficiency or reducing the cost of generating electricity from cogeneration systems [5,6]. When emissions are considered in optimization problems, they are usually based on emissions resulting from the operational phase of energy systems [7,8]. A gap exists in the established literature in assessing the cumulative life cycle environmental impacts that might result from building operation. The potential environmental impacts resulting from energy systems in buildings can be global, such as greenhouse gases, regional, such as acid rain, or local, such as smog formation.

The combination of life cycle environmental impact assessment and operations research presents an alternative approach to evaluating building energy systems. An LCA MILP optimization model was developed to determine the most effective mix of energy system options, including cogeneration systems. The model can also optimize the operation of the energy systems based on environmental as well as economic criteria. When minimizing environmental impact, the emission factors (e.g., the kg of carbon dioxide equivalents per kWh) obtained from the LCA model are used as coefficients of the decision variables (e.g., kWh of electricity from a particular system) in the objective function of the optimization model. Depending on the selection criteria, the objective function can be solved to minimize the life cycle emissions (e.g., GWP, AP, or TOPP), primary energy consumption, or cost that can result from meeting a building's energy demands. Therefore, when evaluating the objective function values, the MILP solution results in the optimal values for the decision variables for the optimum operational strategy [9,10]. The development of the LCA models for the energy systems are presented in this paper.

1 Goal and Scope

The goal of this study is to model selected energy systems that provide space heating and cooling, electricity for lighting and equipment, and domestic hot water in commercial buildings to assess the potential life cycle environmental impacts that might result from the production and use of energy. Both conventional and alternative energy systems are studied. Conventional systems include grid-connected electricity generation utility systems, which typically include a mix of coal-fired steam turbines, nuclear- and large natural gas-fired turbines, and renewable sources; natural gas-fired boilers for space heating; and electric-driven chillers and absorption chillers for space cooling. Alternative energy systems that are covered in this study include different types of natural gas-driven cogeneration systems, and the more efficient NGCC utility-scale power plant. Specifically, the scope of the study includes the average electrical utility generation mix in the USA, an NGCC power plant, an SOFC cogeneration system; a MT cogeneration system; an ICE cogeneration system; and a boiler. Since the daily and annual variability in building load may require that energy systems operate at part load, the cogeneration systems are modeled at part-load operation.

2 Methods

2.1 System boundaries

The study follows ISO guidelines [11]. The stages included in the LCA model are the extraction of raw materials and energy resources, transportation, production, combustion/conversion, and use. Data required for creating the LCA models of these systems encompass primary and secondary raw materials, energy resources, and air emissions resulting from the different stages in the life cycle of these systems. The unit processes are linked together by elementary flows: raw materials and energy entering the processes from the environment, and materials and energy leaving the processes, which are released into the environment. Within the system boundaries, processes are linked together by intermediate product flows, such as auxiliary materials required for construction, auxiliary energy required for operating the process, and transportation required to deliver auxiliary materials/energy to the process.

2.2 Functional unit

The functional unit that is used to measure the performance of the functional outputs of the energy systems modeled in this study is the production of one kWh of energy output. One A kWh of electric energy output is used as the functional unit for the cogeneration systems (SOFC, ICE, and MT), average electric generation mix and NGCC. A kWh of thermal energy output is used as the functional unit for the gas boiler.

2.3 Data and LCI analysis

Data from the literature and commercially available systems, such as boilers and cogeneration systems, are used to define the characteristics of the modeled unit processes, such as energy efficiencies, sizes, weights, compositions, emissions and other relevant characteristics. LCA software, Global Emission Model for Integrated Systems (GEMIS) [12], is used to model the energy systems by defining the characteristics of each unit process and constructing a product system. A detailed description of the life cycle inventories (LCIs) for natural gas production and other fuel production as well as the modeled energy systems are documented in [9].

2.3.1 Cogeneration technologies

(a) Solid oxide fuel cell (SOFC) system

An atmospheric pressure simple cycle cogeneration SOFC system is modeled, which represents an emerging technology in combined heat and power (CHP) applications. Their advantages are low emissions, low noise, modular design, and high efficiency over the load range. Their disadvantages are their high costs and that the fuel requires processing unless pure hydrogen is used [13]. The natural gas-fuelled tubular SOFC system has an electric output of 125 kW, and process heat can be recovered for hot water and heating loads. The entire LCI of the fuel cell consists of the natural gas reformation process, the manufacturing of the SOFC main cell and the balance of plant manufacturing processes, and the use or operation phase of the SOFC.

In the external steam reforming process, natural gas is converted into a gas containing hydrogen and carbon monoxide, with small amounts of water and carbon dioxide. Hydrogen and carbon monoxide obtained from the reforming process is directly used as fuel for the SOFC. The modeled reforming process has a conversion efficiency of 80% of fuel input. The input to the process is natural gas and the direct output consists of an emission from the reforming process of 4.415E-01 kg/kWh of CO_2.

The manufacturing process of the SOFC is complicated and, because it is a new technology, few details are given in literature. Materials, energy requirements and emissions associated with the SOFC manufacturing process are obtained from an LCA study on the manufacturing phase of the SOFC [14]. The manufacturing process of the SOFC consists of two main parts, namely manufacturing the main cell and manufacturing the balance of the plant (BOP). Manufacturing the main cell includes the manufacturing of the two electrodes (anode and cathode), the electrolyte and the interconnect for the SOFC. Manufacturing of the BOP components includes the manufacturing of the process vessel, stack reformer boards, air delivery system, the exhaust gas and heat management system, and the power management and control system. The electric energy used in the manufacturing processes is modeled using USA average electric grid and the heat used in the manufacturing processes is obtained from industrial gas boilers. For the use phase, the operating system performance estimates are modeled based on the CHP125 Siemens Westinghouse SOFC module [15]. The SOFC unit has a lifetime of about 70,100 hours (8 years) if operated 8,760 hours/year. **Table 1** shows the operating characteristics used in creating seven LCA models of the SOFC for the indicated full and part load kW electric output levels.

Table 1: Operating characteristics of the SOFC cogeneration system

Percent Load	Net Electric Output (kW_e)	Electric Efficiency (%)	Thermal Efficiency (%)	Overall Efficiency (%)	Power to Heat Ratio
62%	78	51	21	72	2.43
68%	85	50	24	74	2.08
78%	98	50	28	78	1.79
85%	106	49	30	79	1.63
93%	116	48	32	80	1.50
100%	125	45	35	80	1.29
104%	130	44	37	81	1.19

(b) Microturbine system

Small natural gas-fired microturbines range in sizes between 30 kW–350 kW. Their advantages are the small number of moving parts, compact size, light weight, low emissions, and that no cooling is required; whereas, their disadvantages are their high costs, relatively low mechanical efficiency, and that they are limited to lower temperature cogeneration applications [13]. The characteristics of the microturbine system modeled in this study are based on the microturbine tested for a combined heat and power (CHP) system by the Greenhouse Gas Technology Center (GHG Center) under the Environmental Technology Verification Program (ETV) [16]. Electric power is generated by a microturbine with a nominal power output of 60 kW at standard pressure and temperature. The system operates on natural gas and consists of an air compressor, recuperator, combustor, turbine, and a permanent magnet generator.

The LCI consists of inputs to the MT process including natural gas from the gas pipeline and auxiliary materials used in the construction of the unit process, operation phase of the MT cogeneration system and outputs (air emissions) from the unit processes. The manufacturing process is simplified to the materials required for manufacturing the MT, i.e., cooling systems, water losses and other manufacturing processes of the MT are not included. The manufacturing phase is simplified to the 12,600 kg/MW steel required for manufacturing the MT, while other processes associated with the manufacturing of the MT are not included. The lifetime of the MT unit is about 40,300 hours (4.6 years) if operated 8,760 hours/year. **Table 2** shows the MT system operating characteristics at maximized heat recovery [16], which are used in creating the four LCA MT unit processes for the indicated part load operation characteristics.

Table 2: Operating characteristics of the MT cogeneration system

Percent Load	Net Electric Output (kW_e)	Electric Efficiency (%)	Thermal Efficiency (%)	Overall Efficiency (%)	Power to Heat Ratio
100%	54.9	26	52	78	0.50
75%	39.9	24	56	81	0.43
50%	24.8	20	57	77	0.35
25%	9.8	13	58	71	0.22

(c) Internal combustion engine (ICE) system

Internal combustion engines (ICE) cogeneration systems are usually less than 5 MW. Their advantages are their high power efficiency with part load flexibility, fast start-up, relatively low investment cost, good load following capability, and low-pressure gas operation. Their disadvantages are their high maintenance costs, lower temperature of recovered heat which limits the cogeneration applications, relatively high air emissions, high level of high frequency noise, and a cooling system that is required even if recovered heat is not used [17].

Table 3: Operating characteristics of the ICE cogeneration system

Percent Load	Net Electric Output (kW_e)	Electric Efficiency (%)	Thermal Efficiency (%)	Overall Efficiency (%)	Power to Heat Ratio
100%	172	33.4	54.8	88.3	0.61
75%	129	30.4	57.8	88.2	0.53
50%	87	26.6	60.8	87.4	0.44

In this study, the ICE cogeneration system modeled is 150 kW and operating specifications of the engine are based on commercially available engines [20]. The 150 kW ICE modeled has a lifetime of 45,000 hours (5.1 years) when operating 8,760 hours/year. The manufacturing process that is modeled is simplified to only include the materials required for manufacturing the ICE. The material used in the process is 27,000 kg/MW steel. Operation specifications for the 150 kW ICE process are given in **Table 3**, including part load operation characteristics. A three way catalytic converter is modeled to reduce the emissions resulting from the ICE. The three way catalytic converter reduces oxides of nitrogen (NO_x) emissions by 90%, carbon monoxide (CO) by 50%, and non-methane volatile organic carbons (NMVOC) by 50%.

2.3.2 Grid-based energy systems

(a) USA average electric grid

The electric generation mix in the USA consists of 53% coal, 17% natural gas, 17% nuclear, 9% hydro, 2% oil, 2% waste, 0.4% geothermal and 0.15% wind [18]. An average grid loss of 6.5% is assumed in the process [19]. GEMIS database is used to create models for each of these power plants and to create the average electric generation mix process. The electric conversion efficiency of the average electric generation mix is 32% based on the lower heat value (LHV) of fuel input. Detailed descriptions of the life cycle stages for the USA average electric generation is documented in [9].

(b) NGCC power plant

A 500 MW natural gas-fired combined-cycle power plant (NGCC) with 49% electric conversion efficiency based on fuel input is modeled to represent the most efficient available central power generation technology. Specifications and assumptions for modeling the NGCC process are acquired from a life cycle assessment study of a natural gas combined cycle power generation system [20]. The plant configuration consists of two gas turbines, a three pressure heat recovery steam generator, and a condensing reheat steam turbine. Natural gas is fed into a gas turbine which drives the generator. Waste heat from the turbine is captured by the heat recovery steam generator which provides steam for the steam turbine which, in turn, also drives a generator. In such a system, usually two-thirds of the electric power is provided by the gas turbine and one-third by the steam turbine. The 500 MW NGCC process is modeled with a lifetime of 262,800 hours (30 years) operating 8,760 hours/year. Emission factors used in creating the LCI of the NGCC process are obtained from EPA AP-42 [21].

2.3.3 Gas boiler

The gas boiler model has an output of 1 MW and a lifetime of 20 years operating 4,000 hours/year. The thermal conversion efficiency is 88.7% based on fuel input (LHV). The combustion emissions from the boiler are obtained from EPA's AP-42 [21].

2.4 Assumptions and limitations

The assumptions made in creating these LCA models are:

- Thermal and electric conversion efficiencies of the cogeneration systems are achievable and the generated energy is of utilizable quality;
- The technology will perform as indicated in the literature;
- With respect to geographical and time coverage, this study assesses the current and near future development of cogeneration systems in the US, and the average electric generation mix is modeled based on current average electricity production in the US; and
- No heat or electric loses from the cogeneration processes are considered other than those captured by the conversion efficiencies.

One of the limitations of this LCA study is that the environmental impact indicators used are not representative of comprehensive environmental impact analysis but represent a class of potential environmental impacts representing a global impact category such as GWP, local impact such as TOPP, regional impact such as AP, and an impact that transcends from local to regional and global impact such as PE. These impact categories represent widely used environmental parameters, which could be used for comparative analysis with previous and future studies. A comprehensive environmental impact analysis would be more valuable if the study is done in an actual setting.

2.5 Impact categories

The impact assessment step of the LCA is intended to evaluate the magnitude and significances of potential environmental impacts of the product systems using the results of the life cycle inventory analysis. Impact categories considered in the LCA study to quantify the potential contribution of the product's inventory flow are PE, GWP, AP and TOPP. The main emissions that contribute to GWP [22], AP and TOPP [23] are given in **Table 4**.

Table 4: Equivalent Factors for GWP, AP and TOPP

GWP (kg of CO_2 equivalents)					
CO_2	CH_4	N_2O	Perfluoromethane	Perfluoroethane	
1	21	316	6500	9200	
AP (kg of SO_2 equivalents)					
NOx	**SO_2**	**HCL**	**HF**	**H_2S**	**NH_3**
0.696	1.0	0.878	1.601	0.983	3.762
TOPP (kg of TOPP equivalents)					
CH_4	**NO_x**	**NMVOC**	**CO**		
0.014	1.22	1.0	0.11		

3 Results and Discussion

The environmental impact indicators identified in the life cycle impact assessment step are used in the assessment of the potential environmental impacts resulting from the modeled energy systems when used to produce the functional unit of one kWh of energy. All the environmental factors are calculated based on the lower heat value (LHV) of fuel input. Note that for all systems, the functional unit is the production of one kWh of electric energy except for the gas boiler where the functional unit is the production of one kWh output of thermal energy.

3.1 Primary energy consumption

The LCA results indicate that the total PE consumption factor values increase with decreasing percent load operation. This follows the power to heat ratio values as they decrease with decreasing part load operation for both the MT and ICE cogeneration systems. In other words, the MT and ICE systems have the lowest PE factor at full operating load. For the SOFC, the PE factor is approximately constant at the modeled part load operations but, unlike the MT and ICE systems, it shows a slight decrease in the total PE factors with decreasing part load operation. This is due to a slight increase in power to heat ratio. **Table 5** includes the total life cycle PE factors obtained from the energy systems when used to produce a unit output of electrical energy. The SOFC has the lowest PE factors amongst the cogeneration systems followed by the ICE and finally the MT cogeneration system because of the higher power to heat ratio of the SOFC. The NGCC power plant has the lowest overall PE consumption factor, which is comparable to the SOFC cogeneration system factors. The PE consumption factor of the average electric grid is 32% higher than that of the NGCC but is comparable to the PE consumption factor resulting from the ICE when operated at full load. **Table 6** shows the PE consumption factor for the gas boiler when used to produce a unit output of thermal energy.

3.2 Global warming potential

Table 7 shows the GWP indicator values and **Fig. 1** (see overleaf) shows an illustration of these values and the major gas contribution for the GWP factors resulting from the energy systems when used to produce the functional unit of electrical energy. Note that the values shown in the figures are for the cogeneration systems operating at 100% load. The LCA results show that, similar to the PE consumption factors, the GWP factors increase with decreasing part load operation for both MT and ICE cogeneration systems. GWP emissions are higher due to inefficient fuel combustion at lower part load

Table 5: Life cycle PE consumption factors of the energy systems

System		PE Consumption (kWh/kWh_e)
MT	MT 100% Load	3.99E+00
	MT 75% Load	4.32E+00
	MT 50% Load	5.22E+00
	MT 25% Load	7.97E+00
ICE	ICE 100% Load	3.13E+00
	ICE 75% Load	3.44E+00
	ICE 50% Load	3.93E+00
SOFC	SOFC 104% Load	3.00E+00
	SOFC 100% Load	2.93E+00
	SOFC 93% Load	2.75E+00
	SOFC 85% Load	2.69E+00
	SOFC 78% Load	2.64E+00
	SOFC 68% Load	2.64E+00
	SOFC 62% Load	2.59E+00
US Average Electric		3.09E+00
NGCC		2.27E+00

Table 7: Life cycle GWP emission factors for the energy systems

System		GWP-Factor	Co_2	CH_4	N_2O
		(kg/kWh_e)			
MT	MT 100% Load	7.50E-01	7.33E-01	7.52E-04	1.55E-06
	MT 75% Load	7.95E-01	7.70E-01	1.16E-03	1.68E-06
	MT 50% Load	1.07E+00	8.96E-01	8.09E-03	2.03E-06
	MT 25% Load	1.48E+00	1.38E+00	4.51E-03	3.10E-06
ICE	ICE 100% Load	6.20E-01	5.39E-01	3.84E-03	1.22E-06
	ICE 75% Load	6.75E-01	5.92E-01	3.91E-03	1.34E-06
	ICE 50% Load	7.64E-01	6.77E-01	4.14E-03	1.53E-06
SOFC	SOFC 104% Load	1.05E+00	1.03E+00	5.87E-04	1.35E-06
	SOFC 100% Load	1.02E+00	1.01E+00	5.75E-04	1.33E-06
	SOFC 93% Load	9.61E-01	9.49E-01	5.41E-04	1.25E-06
	SOFC 85% Load	9.41E-01	9.30E-01	5.31E-04	1.23E-06
	SOFC 78% Load	9.23E-01	9.11E-01	5.21E-04	1.21E-06
	SOFC 68% Load	9.23E-01	9.11E-01	5.21E-04	1.21E-06
	SOFC 62% Load	9.05E-01	8.94E-01	5.11E-04	1.19E-06
US Average Electric		7.87E-01	7.36E-01	1.82E-03	4.03E-05
NGCC		4.45E-01	4.31E-01	4.56E-04	1.21E-05

Table 6: Life cycle environmental factors for the gas boiler

PE (kWh/kWh_t)	PE Consumption Usage Factor				
	1.18E+00				
GWP (kg/kWh_t)	**GWP Factor**	**CO_2**	**CH_4**	**N_2O**	
	2.40E-01	2.35E-01	2.24E-04	1.55E-06	
AP (kg/kWh_t)	**AP Factor**	**SO_2**	**NO_x**		
	9.89E-05	4.83E-06	1.35E-04		
TOPP (kg/kWh_t)	**TOPP Factor**	**NO_x**	**CO**	**NMVOC**	**CH_4**
	2.09E-04	1.35E-04	1.74E-04	2.25E-05	2.24E-04

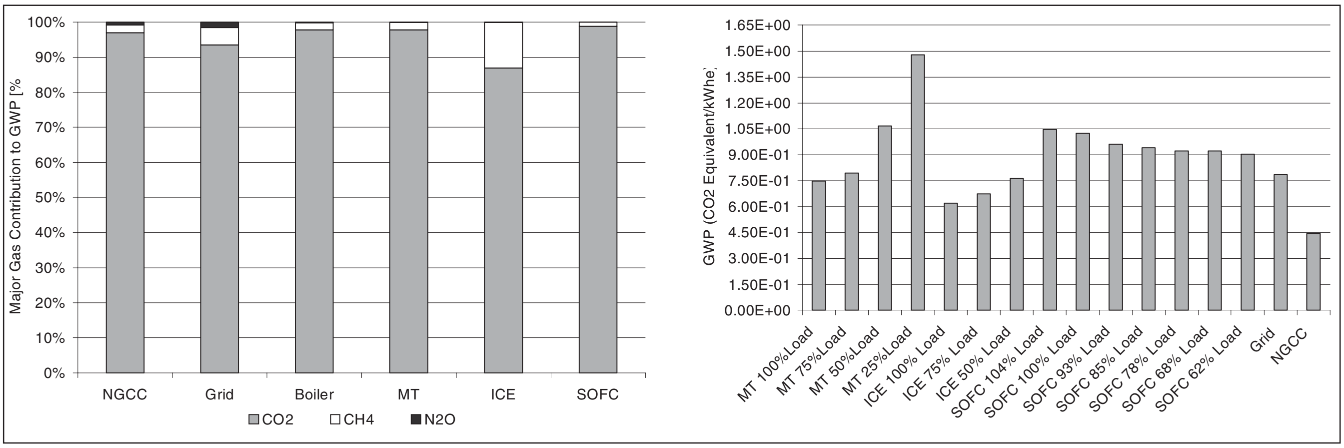

Fig. 1: Illustration of the GWP indicator values and the major gas contribution for the GWP factors resulting from the energy systems when used to produce the functional unit of electrical energy

operation. Table 6 shows the GWP indicator value for the gas boiler when used to produce a unit output of thermal energy.

For the SOFC cogeneration system, the GWP factors are approximately constant at the different part loads but decrease slightly with decreasing part load operation. The SOFC has the highest GWP values while the ICE cogeneration system has the lowest GWP values compared to the other cogeneration systems. The reason for the high GWP value for the SOFC cogeneration system is because of its relatively high CO_2 emissions, which contribute 99% to the GWP value, and which originate from steam reforming natural gas. CH_4 and N_2O contribute only 1% and 0.0004%, respectively, to the SOFC GWP factor. On the other hand, the major source of CO_2 emissions from the ICE and MT cogeneration systems, (which contributes 87% and 98%, respectively, of their GWP factors), is due to fuel combustion in the use phase, while a small percentage of CO_2 emissions originate from other upstream manufacturing processes. CH_4 emissions from the ICE system contribute about 13% of its GWP value, where 85% of the emissions are from the use phase and the remaining 15% originate from upstream processes, such as manufacturing processes and gas processing and extraction. CH_4 and N_2O emissions from the MT system have a small contribution to its GWP value, where the emissions originate mainly from manufacturing phase and other upstream processes associated with natural gas extraction and processing.

Compared to other systems, the NGCC power plant has the lowest GWP per kWh. The GWP of the average electric grid is about 77% higher than that of the NGCC power plant and is comparable to the MT operating at full load. The CO_2, CH_4 and N_2O emissions contribute about 97%, 7% and 1%, respectively, to the NGCC power plant GWP value, where most of these emissions result from fuel combustion for power production from the NGCC and the remaining emissions originate from upstream manufacturing processes. For the average electric grid, the CO_2, CH_4 and N_2O emissions contribute about 94%, 5% and 1%, respectively, to its total GWP value, where power generation from the coal-driven power plant is responsible for most of the CO_2 and CH_4 emissions. For the gas boiler, the CO_2, CH_4 and N_2O emissions contribute about 97%, 2% and 0.2%, respectively, to its GWP value, where the majority of the CO_2 and N_2O emissions originate from the use phase, whereas most of the CH_4 emissions originate from gas extraction and processing.

3.3 Acidification potential

Table 8 shows the AP indicator values and **Fig. 2** shows an illustration of these factors and the major contributions to

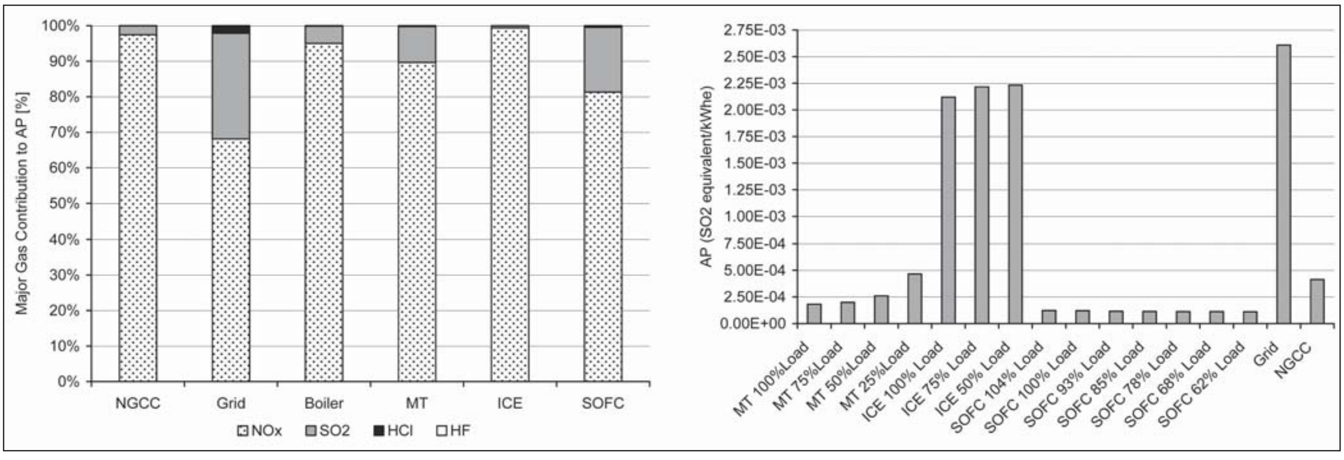

Fig. 2: Illustration of the AP indicator factors and the major contributions to AP from the energy systems for 1 kWh of energy with the cogeneration systems operating at 100% load

Table 8: Life cycle AP emissions factors for the energy systems

System		AP Factor	SO_2	NO_x
		(kg/kWh$_e$)		
MT	MT 100% Load	1.82E-04	1.83E-05	2.34E-04
	MT 75% Load	1.99E-04	1.98E-05	2.57E-04
	MT 50% Load	2.60E-04	2.38E-05	3.38E-04
	MT 25% Load	4.67E-04	3.59E-05	6.17E-04
ICE	ICE 100% Load	2.12E-03	1.34E-05	3.03E-03
	ICE 75% Load	2.22E-03	1.45E-05	3.16E-03
	ICE 50% Load	2.23E-03	1.57E-05	3.18E-03
SOFC	SOFC 104% Load	1.23E-04	2.22E-05	1.44E-04
	SOFC 100% Load	1.21E-04	2.20E-05	1.41E-04
	SOFC 93% Load	1.15E-04	2.15E-05	1.34E-04
	SOFC 85% Load	1.13E-04	2.13E-05	1.31E-04
	SOFC 78% Load	1.12E-04	2.12E-05	1.29E-04
	SOFC 68% Load	1.12E-04	2.12E-05	1.29E-04
	SOFC 62% Load	1.10E-04	2.10E-05	1.27E-04
US Average Electric		2.61E-03	7.77E-04	2.55E-03
NGCC		4.14E-04	1.04E-05	5.80E-04

AP from the energy systems for 1 kWh of energy with the cogeneration systems operating at 100% load. Table 6 shows the AP indicator value for the gas boiler when used to produce a unit output of thermal energy. The high AP indicator values of the ICE cogeneration system compared to the MT and the SOFC cogeneration systems (about 92% higher) are because of the higher NO_x emissions from the ICE cogeneration system relative to the MT and SOFC cogeneration systems. The average electric grid has a comparable AP indicator value to the ICE cogeneration system, whereas the AP value of the NGCC is about 84% lower than that of the average electric grid.

The NO_x emissions contribute about 81% to the AP factor of the SOFC cogeneration system, where only 0.4% of the NO_x emissions are due to the SOFC use phase and the remaining 99.4% of the NO_x emissions are associated with upstream manufacturing processes of the SOFC and fuel production. On the other hand, most of the NO_x emissions from the ICE cogeneration system, which contribute 99% of its AP value, result from fuel combustion during the use phase. Unlike the ICE, only 29% of the NO_x emissions, (which contribute 90% of the MT AP factor), result from the use phase of the MT and the remaining 71% of NO_x emissions originate mostly from upstream processes associated with natural gas production. SO_2 emissions minimal contributions to the AP values of the cogeneration systems, and most of the SO_2 emissions originate from upstream manufacturing and fuel production processes.

For the NGCC power plant, NO_x emissions represent about 97% of its AP factor. Most of the NO_x emissions are from the NGCC fuel combustion process and the rest of the NO_x emissions originate from other upstream NGCC manufacturing processes and fuel production. For the average electric grid, NO_x emissions contribute about 68% to its AP value, where 59% of the NO_x emissions are due to electricity production from the coal steam-driven power plant, 30% from the gas-driven power plant, 4% from the waste steam-driven power plant, and the remaining 7% are associated with other upstream fuel and material production. While SO_2 emissions contribute only about 2.5% of the NGCC AP factor, they contribute about 30% of the electric grid AP factor originating mainly from upstream coal production processes used in electricity generation.

For the gas boiler, NO_x emissions contribute about 95% to its AP value, where 64% of the NO_x emissions are from the use phase while 36% of the NO_x emissions are associated with upstream manufacturing processes of the gas boiler and fuel production. SO_2 emissions contribute about 5% of the total AP value of the gas boiler, where 21% of the SO_2 emissions are due to the use phase and the remaining 79% result from upstream processes.

3.4 Tropospheric ozone precursor potential

The LCA results show that while the TOPP indicator factors increase with decreasing part load operation for ICE cogeneration systems, the TOPP values for the MT cogeneration system show a different trend. The values are lowest when the MT cogeneration system is operated at 100% and 75% part load, but the values increase by almost seven times when the MT is operated at 50% load and then decrease almost by half at 25% load operation relative to the values obtained at 50% part load operation. This is because the CO, NMVOC and CH_4 values show inverse relations to NO_x: as the NO_x values increase with decreasing part load operation, the CO, NMVOC and CH_4 values decrease from 50% to 25% part load operation of the MT, resulting in the irregular trend of the TOPP values with part load operation.

Table 9 (see overleaf) shows the TOPP indicator factors and **Fig. 3** (see overleaf) shows an illustration of these factors and the major gas contribution to the TOPP factors resulting from the energy systems when used to produce unit output of electrical energy. Table 6 shows the TOPP indicator value for the gas boiler when used to produce a unit output of thermal energy. The origins of NO_x emissions are the same as discussed in the AP section and the origins of CH_4 emissions are the same as discussed in the GWP section.

The high TOPP indicator values of the ICE cogeneration system compared to the MT and the SOFC cogeneration systems (about 92% higher) is because of the higher NO_x emissions from the ICE cogeneration system relative to the MT and the SOFC systems. However, because the values of CO, CH_4 and NMVOC were relatively high for the MT cogeneration system operating at 50% part load, the resultant TOPP value was higher than any of the other systems. The electric grid has a comparable TOPP indicator value to the ICE cogeneration system, whereas the TOPP value of the NGCC is about 78% lower than that of the average electric grid.

While NO_x has the highest contribution to the SOFC TOPP factor (84%), the NMVOC and CO emissions contribute about 3% and 9%, respectively, to its TOPP value, where

Table 9: Life cycle TOPP emission factors for the energy systems

System		TOPP Factor	NO_x	CO	NMVOC	CH_4
		(kg/kWh$_e$)				
MT	MT 100% Load	3.19E-04	2.34E-04	1.46E-04	7.69E-06	7.52E-04
	MT 75% Load	8.11E-04	2.57E-04	2.30E-03	2.27E-04	1.16E-03
	MT 50% Load	6.39E-03	3.38E-04	1.04E-02	4.72E-03	8.09E-03
	MT 25% Load	3.77E-03	6.17E-04	9.17E-03	1.94E-03	4.51E-03
ICE	ICE 100% Load	4.19E-03	3.03E-03	1.17E-03	3.16E-04	3.84E-03
	ICE 75% Load	4.37E-03	3.16E-03	1.18E-03	3.23E-04	3.91E-03
	ICE 50% Load	4.40E-03	3.18E-03	1.26E-03	3.18E-04	4.14E-03
SOFC	SOFC 104% Load	2.08E-04	1.44E-04	1.61E-04	6.59E-06	5.87E-04
	SOFC 100% Load	2.04E-04	1.41E-04	1.59E-04	6.48E-06	5.75E-04
	SOFC 93% Load	1.94E-04	1.34E-04	1.55E-04	6.17E-06	5.41E-04
	SOFC 85% Load	1.91E-04	1.31E-04	1.54E-04	6.08E-06	5.31E-04
	SOFC 78% Load	1.87E-04	1.29E-04	1.53E-04	5.99E-06	5.21E-04
	SOFC 68% Load	1.87E-04	1.29E-04	1.53E-04	5.99E-06	5.21E-04
	SOFC 62% Load	1.85E-04	1.27E-04	1.51E-04	5.90E-06	5.11E-04
US Average Electric		3.46E-03	2.55E-03	6.30E-04	2.48E-04	1.82E-03
NGCC		7.69E-04	5.80E-04	1.67E-04	3.71E-05	4.56E-04

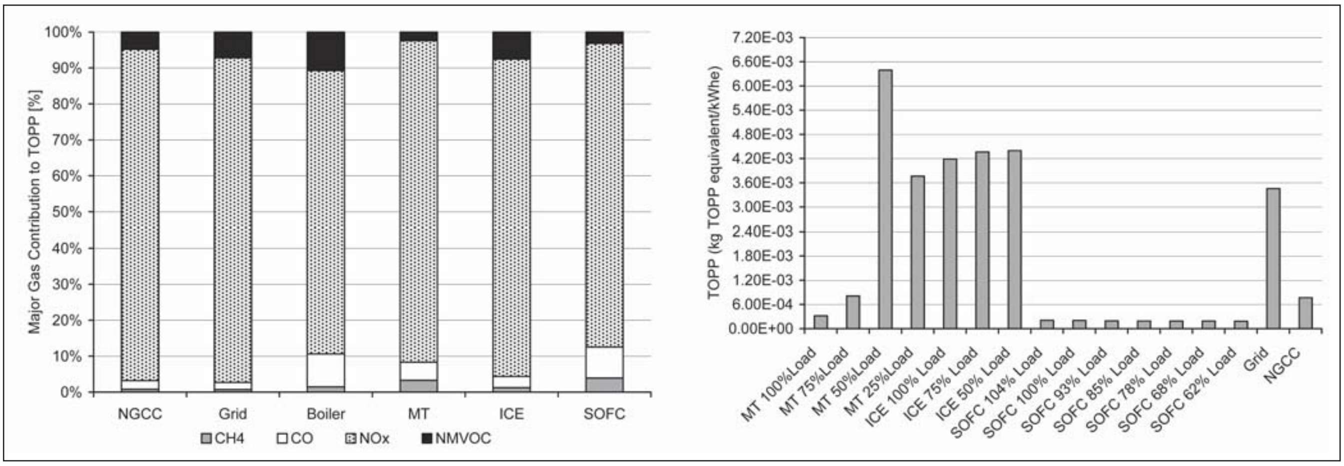

Fig. 3: Illustration of the TOPP indicator factors and the major gas contribution to the TOPP factors resulting from the energy systems when used to produce unit output of electrical energy

the majority of the emissions originate from the upstream SOFC manufacturing phase. CH_4 contributes only about 4% to the SOFC TOPP value. Unlike the SOFC, most of the origins of the NMVOC and CO emissions of the ICE co-generation system are from the use phase, contributing about 8% and 3%, respectively, to its TOPP value. NO_x and CH_4 contribute about 88% and 1%, respectively, to the total TOPP value of the ICE system. NMVOC and CO emissions contribute about 2% and 5%, respectively, to the total TOPP value of the MT system, where most of the emissions originate from upstream processes. NO_x and CH_4 contribute about 89% and 3%, respectively, to the total TOPP value of the MT system. NO_x emissions has the highest contribution to the TOPP factors for both the electric grid and the NGCC, as well as the gas boiler, while the NMVOC and CO emissions have a low share in their TOPP values.

4 Conclusions

Life cycle assessments were performed to evaluate the life cycle emission factors of energy systems that can be used to meet the energy demand of a building. Cogeneration systems produce utilizable thermal energy when used to meet a certain electrical demand which can make them an attractive alternative to conventional systems. The analysis of the results indicates that the electrical to thermal energy production ratio has a direct influence on the value of the life cycle primary energy consumption factors. Energy systems with high electrical to thermal production ratios (such as the solid oxide fuel cell) have low primary energy consumption factors. In the case of global warming potential, the values of the life cycle global warming potential obtained from the energy systems do not only depend on the efficiencies of the systems but also the origins of emissions contributing to the global warming potential. For instance, although

the solid oxide fuel cell cogeneration system has a high electrical efficiency ratio compared to the other systems, it has relatively high global warming potential factor due to large quantities of CO_2 produced from the natural gas reforming process. On the other hand, the global warming potential values of the other energy systems result mainly from the contribution of emissions from the use phase.

When evaluating the life cycle acidification and tropospheric ozone potentials, the types of fuel as well as the combustion characteristics of the energy systems are the main factors that influence the values of the acidification potential. For instance, the high acidification potential and tropospheric ozone potential of the electric grid is mainly because of the contribution of the NO_x and SO_2 emissions, where the majority of these emissions originate from power production from the coal-driven power plant. On the other hand, since the natural gas combined cycle and cogeneration systems are all natural gas driven, the combustion characteristics of these systems influence the values of the acidification potential and tropospheric ozone potential. For example, the relatively high acidification potential of the internal combustion engine cogeneration system is due to the contribution of the high NO_x values resulting from the use phase of the internal combustion engine, whereas the microturbine and solid oxide fuel cell cogeneration systems have relatively low acidification potential factors because of their low NO_x emissions, which is consistent with conclusions by [24], where the majority of their emissions result from upstream processes.

5 Recommendations and Perspectives

The emission factors obtained from this LCA study are used for coefficients of decision variables in the formulation of a MILP that can be used to optimize the selection and operation of energy systems based on environmental criteria. The model considers factors such as systems efficiencies, emission characteristics, part load operation and building's energy demands. Therefore, the values of the emission factors presented here should not be regarded as the only criteria for choosing the technology that could result in lower environmental impacts, but rather one aspect that might contribute to the design of an optimum energy system for a commercial building.

References

[1] Arivalagan A, Raghavendra B-G, Rao A-K (1995): Integrated energy optimization model for a cogeneration based energy supply system in the process industry. Electrical Power & Energy Systems 17, 227–233

[2] Benelmir R, Feidt M (1998): Energy Cogeneration Systems and Energy Management Strategy. Energy Conversion and Management 39, 1791–1802

[3] Marechal F, Kalitventzeff B (1998): Process integration: Selection of the optimal utility system. Computers Chem Eng 22, S149–S156

[4] Kamimura K, Mukai T, Nishi Y, Yokoyama R-K-I (1999): Development of an Optimal Operational Planning System Using an Object-Oriented Framework for Energy Supply Plants. Sixth International IBPSA Conference, Building Simulation, Kyoto, Japan

[5] Riensche E, Stimming U, Unverzagt G (1998): Optimization of a 200 kW SOFC cogeneration power plant. Part I: Variation of process parameters. Journal of Power Sources 73, 251–256

[6] Yilmaz T (2004): Optimization of cogeneration systems under alternative performance criteria. Energy Conversion and Management 45, 939–945

[7] Chung W, Wu J-Y, Fuller J (1997): Dynamic energy and environment equilibrium model for the assessment of CO_2 emission control in Canada and the USA. Energy Economics 19, 103–124

[8] Wu J-Y, Rosen A-M (1999): Assessing and optimizing the economic and environmental impacts of cogeneration/district energy systems using an energy equilibrium model. Applied Energy 62, 141–154

[9] Osman A (2006): Life cycle optimization model for integrated cogeneration and energy systems applications in buildings. Dissertation. Dept. of Civil and Environmental Engineering, University of Pittsburgh, Pittsburgh, Pennsylvania

[10] Osman A-E, Ries R (2006): Optimization for cogeneration systems in buildings based on life cycle assessment. ITcon 11, 269–284

[11] ISO (1997): Environment Management – Life Cycle Assessment Principles and Framework. International Standardization Organization, Ann Arbor, MI, USA

[12] Fritsche UR, Schmidt K (2003): GEMIS manual. Institute for Applied Ecology, Freiburg, Germany

[13] EPA (2002): Catalogue of CHP Technologies. U.S Environmental Protection Agency. Combined Heat and Power Partnership, <www.epa.gov/CHP/pdf/catalog_entire.pdf>

[14] Siemens (2005): SFC-200 performance. Siemens, Inc., Pittsburgh, PA, USA, <http://www.powergeneration.siemens.com/en/fuelcells/commercialization/sfc200/index.cfm>

[15] Karakoussis V, Leach M, Vorst V-D-R, Hart D, Lane J, Pearson P, Kilner J (2000): Environmental Emissions of SOFC and SPFC System Manufacture and Disposal. Imperial College of Science, Technology and Medicine, Crown, UK

[16] USEPA-GHG (2003): Environmental Technology Verification Report: Combined Heat and Power at a Commercial Supermarket-Capstone 60 kW Microturbine CHP System. U.S. Environmental Protection Agency and Greenhouse Gas Technology Center, Southern Research Institute

[17] Caterpillar Inc. (1999): Gas engine technical data: G3304 NA. Caterpillar Inc., Peoria, IL, USA

[18] IEA (1998): World Energy Outlook: Electricity Information. International Energy Agency, IEA Books, Paris, France

[19] EIA (2002): Monthly Energy Review: April 2002. U.S. Energy Information Administration, <http://www.eia.doe.gov>

[20] Spath P, Mann M (2000): Life Cycle Assessment of Natural Gas Combined-Cycle Power Generation System. U.S. Dept. of Energy, Office of Scientific and Technical Information. Oak Ridge, TN, USA

[21] EPA (1995): Compilation of air pollutant emission factors: AP-42: Stationary Point and Area Sources. U.S. Environmental Protection Agency, <http://www.epa.gov/ttn/chief/ap42>

[22] IPCC (1996): Climate change 1995: The science of climate change. Cambridge University Press, Cambridge, UK

[23] EEA (2000): Environmental Signals 2000. European Environmental Agency, Copenhagen, Denmark

[24] Pehnt M (2003): Assessing Future Energy and Transport Systems: The Case of Fuel Cells. Part 2: Environmental Performance Int J LCA 8, 365–378

Received: May 27th, 2006
Accepted: February 25th, 2007
OnlineFirst: February 26th, 2007